

Spatial and Temporal Characteristics of Saline Springs: Sea of Galilee, Israel

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Abstract

Spatial and temporal characteristics of the saline springs that emerge along the western shore of the Sea of Galilee (Lake Kinneret) are analyzed. Three groups of onshore springs (Tiberias, Fuliya, and Tabgha) and two groups of offshore springs (Barbutim and Maagan), contribute saline water to the lake with concentrations in the range of 300 to 18,000 mgCl/L, depending on location and season. It is well accepted that water emerging from these springs is a mixture of two endmembers: deep-seated saline ground water and shallow, fresh circulating ground water. Temporal trends of discharge rates and of chloride (representing the deep saline aquifer) and nitrate (representing the shallow fresh water aquifer) concentrations within each group of springs are presented. Results show the proportions of the two water bodies while mixing are time dependent. Discharge and concentration peaks in Tabgha springs precede those in Fuliya and Tiberias springs by approximately two months. An analytical solution shows that in Tabgha, variations of these parameters are mainly controlled by recharge variations in the Galilee, and follow an exponential function. In Fuliya and Tiberias, variations of these parameters are mainly dependent on lake level, and follow a sine-cosine function. The different patterns are attributed to different hydraulic properties of the discharge area.

Introduction

The Sea of Galilee (Lake Kinneret) is the lowest fresh water lake on earth, located within a deep pull-apart basin (Figure 1) in the northern part of the Dead Sea Transform (Freund et al. 1970; Garfunkel 1981; Ben-Avraham et al. 1996). Its area is approximately 170 km² and its maximum water depth is 47 m (Ben-Avraham et al. 1990). Water surface level fluctuates seasonally, having an average elevation of -210 m below mean sea level (MSL).

Most water input to the lake comes from the Jordan River and some ephemeral streams with a salinity (herein expressed as Cl concentration) of 10 to 30 mg/L. Chloride concentration of the lake was about 400 mg/L prior to the construction of a saline water aqueduct in 1965, diverting some of the saline springs. Since then, it decreased drastically until 1969, and ever since varies between 190 and 250 mgCl/L. The order of magnitude concentration difference between the major inlets and the lake is a result of salt flux from two major sources: (1) saline springs having chloride concentration between 300 and 18,000 mg/L (onshore: Tiberias, Fuliya, and Tabgha, and offshore: Barbutim and Maagan; Figure 1), and (2) diffusional seepage from the bottom of the lake (Stiller et al. 1975; Simon and Mero 1992; Stiller 1994). The present average annual contribution of all sources is estimated to be 146,000 tons of chloride (Simon and Mero 1992), of which 90,000 tons are ungauged (Smith et al. 1989).

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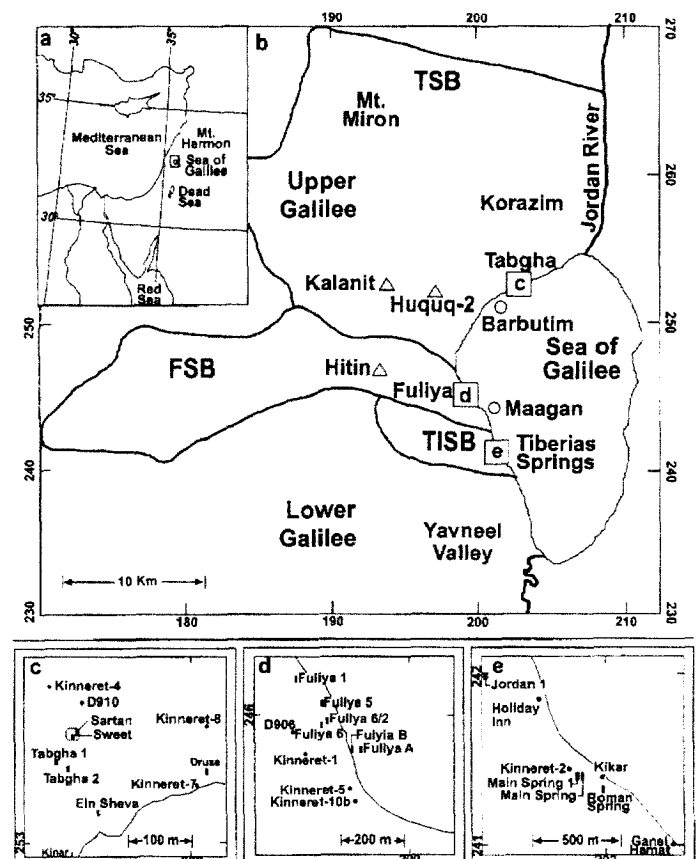


Figure 1. Location maps. (a) The study area. (b) The Sea of Galilee and the three drainage sub-basins: Tabgha (TSB), Fuliya (FSB), and Tiberias (TISB); onshore springs (squares); offshore springs (circles); and wells in the recharge area (triangles). (c) Springs (squares) and wells (circles) in the Tabgha Group. (d) Springs and wells in the Fuliya Group. (e) Springs and wells in the Tiberias Group.

The lake supplies about 30% of Israel's annual water consumption and the high salinity poses a major problem. Therefore, intensive research has been carried out in the past decades to understand the salinization processes. It is well accepted that water emerging at the springs is a mixture of two endmembers, deep-seated saline ground water and shallow fresh circulating ground water (Goldshmidt et al. 1967; Arad and Bein 1986; Gvirtzman et al. 1997a; Bergelson et al. 1998, 1999). However, for many years it was a matter of debate regarding the forces acting on the saline water, and how, where, and in what proportions do the two water bodies mix.

Two generic conceptual models were proposed to assess the problem of saline water ascent to the springs. Mero and Mandel (1963), Mero and Zaltzman (1967), and Mazor and Mero (1969) hypothesized that the deep saline ground water is under overpressure conditions, which results in its ascent to the surface where it mixes with shallow circulating ground water. According to this "self potential" model, overpressure is generated either by compaction of sediments, active tectonic stresses, or a geothermal source. The implication of this hypothesis is that fresh ground water heads in the Galilee should not be decreased (by pumping), as this will increase the proportion of the saline water component entering the lake.

On the other hand, Goldshmidt et al. (1967) and Gvirtzman et al. (1997a, 1997b) proposed that gravity-driven flow plays the major role forcing saline ground water emergence at springs along the Sea of Galilee. According to this "leaching" model, fresh ground water recharged into deep aquifers in the elevated Galilee Mountains applies pressure on the saline ground water. This hypothesis stated that reducing hydraulic heads in deep aquifers in the Galilee (by pumping) will lead to reduction of the pressure applied on the saline ground water. Therefore salt flux into the lake will decrease (see Figure 2 in Gvirtzman et al. [1997a] for a schematic description of the different models).

In this study, we present several parameters associated with springs and wells on the western shore of the Sea of Galilee, collected between 1990 and 1997. Although many detailed geochemical studies were carried in the past, this is the first attempt to use nitrate (NO_3) as a tracer. Although NO_3 is not a good tracer in most natural systems because of its biological transformations, the data presented in this study indicates that its temporal fluctuations are significant. This approach enables independent tracing of the saline and fresh components, and thereby, a quantitative analysis of the mixing process between the two sources. An analytical solution to a set of differential equations, describing the time dependent discharge of the saline ground water and its dilution, is proposed. This approach enables us to highlight the salinization mechanisms, which were not reported previously.

Hydrogeology

The Sea of Galilee is located within a basin capped by a Miocene to Quaternary sequence consisting of fluvial and lacustrine clastics and carbonates, basalts and evaporates more than 4 km (Marcus and Slager 1985), and probably as much as 7 km thick (Ben-Avraham et al. 1996). This thick sequence acts as an aquitard-aquiclude, leading to discharge of ground water from regional aquifers along the margins of the basin.

The recharge area of the regional aquifers in the Galilee (Figure 1b) is located at elevations of up to ~1200 m above MSL (Mt. Miron). Maximum fresh ground water levels are approxi-

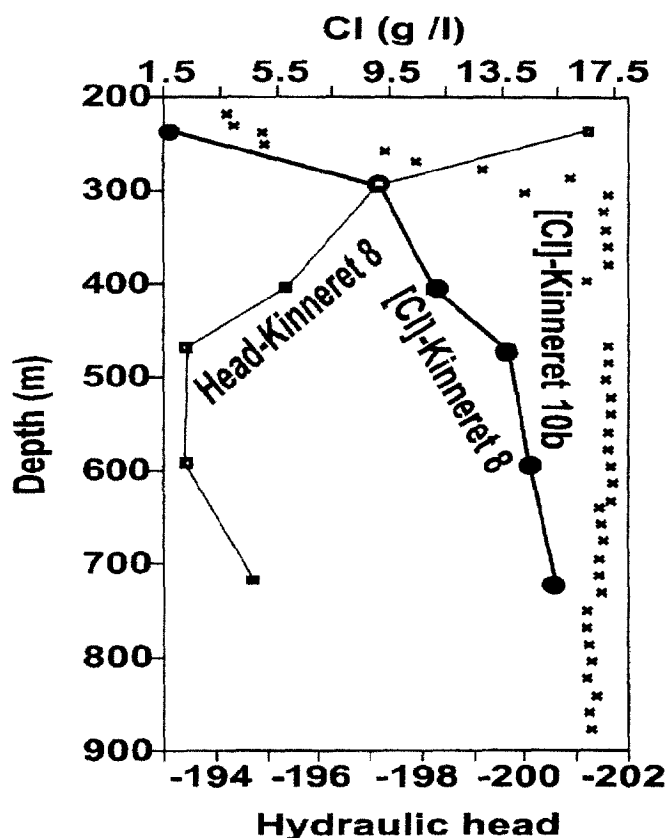


Figure 2. Chloride concentration in the Kinneret-10b well in Fuliya (crosses) and in the Kinneret-8 well in Tabgha (circles) and the hydraulic head in the Kinneret-8 well (squares) (after Michelson et al. 1995).

mately 320 m above MSL. The recharge area is divided into three sub-basins (TSB, FSB, and TISB; Figure 1b) separated from each other by major faults which partially limit flow between them (Michelson 1975). The major aquifers in the Galilee are located in the following units:

1. The deep Jurassic Arad group, which is confined throughout the Galilee. Flow in this aquifer is probably negligible (Gvirtzman et al. 1997a).
2. The Lower Cretaceous Kurnub group with a phreatic area of ~10 km². The exposures contain mainly marl and limestone and are in areas with a sharp relief. This implies that direct recharge into this aquifer is probably small.
3. The Upper Cretaceous Judea Group (JGA) of mainly dolomite and limestone constitutes the major recharge area of the springs. In the Tiberias sub-basin (TSB), recharge takes place in an area of several km². Most recharge probably takes place by leakage from the above basaltic aquifer into the JGA. In the Fuliya (FSB) and Tabgha (TSB) sub-basins, the phreatic part of the aquifer covers approximately 85 and 250 km², respectively. In some areas in the Galilee the aquifer is divided into two sub-aquifers separated by an aquitard of the Dir-Hana formation (Bein 1967; Michelson 1975). In other locations, the aquifer has vertical continuity.
4. The Eocene Avdat group of karstic limestone has a phreatic area of approximately 10 and 57 km² in the Fuliya and Tabgha sub-basins, respectively. In the Tiberias sub-basin the aquifer is not exposed at the surface.
5. The basaltic aquifer of Neogene age in the Eastern Galilee is annually drained by some springs and wells in the Yavneel

Valley (Figure 1b) and surroundings. In Korazim Plateau to the north of the lake (Figure 1b), the aquifer is a few hundred meters thick and has an area of approximately 75 km². At least part of the aquifer in that area is probably drained by the Tabgha springs.

The mixing between the saline and fresh ground water components probably takes place in a limited depth and lateral (east-west) zone. Similar salinity patterns with depth were observed in deep wells in Fuliya and Tabgha. The chloride concentration in observation well Kinneret-10b in Fuliya (Figure 1d) and Kinneret-8 in Tabgha (Figure 1c) changes between 200 and 500 m, whereas below this depth the concentration is nearly constant (15,000 to 18,000 mgCl/L) (Figure 2). Although there is no lithological evidence, the sharp gradient in Tabgha and Fuliya, within the upper parts of the JGA, may define a low hydraulic conductivity unit separating two aquifers: a deep confined aquifer with high and constant chloride concentration, and a shallower aquifer where mixing between the saline water and circulating meteoric water takes

place. The hydraulic head distribution in Kinneret-8 (Figure 2) clearly indicates that flow is from the deep saline aquifer to the shallow fresh water aquifer. In Tiberias, a constant concentration of 15,000 to 18,000 mgCl/L from the surface indicates that mixing probably does not occur.

The saline water in the deep aquifer is probably also limited in a narrow zone (east-west direction) near the lake's shore. This concept is supported by evidence from Kalanit-1,2 and Hitin-2,4 wells which penetrate the lower JGA, and are located only a few km west of the lake. In these wells, pumped water has a chloride concentration lower than 100 mg/L (Bergelson et al. 1999).

Methods

Water samples were collected and analyzed by the Mekoroth Water Co. between the years 1989 and 1997. The data include daily lake levels, weekly spring discharges, chloride and nitrate concentrations in springs, and hydraulic heads in observation wells (Table 1). Partial data from previous years collected by the Tahal

Table 1
Summary of the Data Collected in Springs and Wells During the Years 1989–1997

Name	Type*	Aquifer**	Depth (m)	Hydraulic Head (m)	Discharge (m ³ /sec)	NO ₃ (mg/L)	Cl (mg/L)
Tabgha							
Sweet Spring	OS					1.5–3.6	1000–2500
Druze Spring	OS					1.5–4.0	800–2000
Tabgha-1	OS					1.5–5.0	300–1800
Tabgha 2	OS					1.5–5.0	300–1800
Sartan Spring	OS					0.3–3.0	1000–3800
Ein Sheva	OS				0.01–0.06	1.5–5.0	300–1600
Kinneret-7	AW	UJG	106		0.10–0.20	2.2–5.5	100–1300
Huquq 2	PW	AG	150		0.35–1.00	5.0–7.5	80–110
Ein-Kinar	OS					3.0–7.0	30–50
Kinneret-8	OW	LJG	715	(–190.0)–(–198.0)			
D910	OW	UJG	40	(–202.9)–(–203.1)			
Fuliya							
Fuliya 1	OS					2.5–5.0	100–1200
Fuliya 6	OS				0–0.3	2.5–5.0	500–1500
Fuliya 6/2	OS				0–0.23	2.5–4.0	900–1500
Fuliya 5	OS				0.007–0.028	2.5–4.0	500–1400
Fuliya A ¹	OF			(–209.0)–(–211.5)		0–2.0	2000–3000
Fuliya B ¹	OF			(–209.5)–(–211.0)		2–3.5	1200–1500
D906	OW	UJG	50	(–207.8)–(–209.2)			
Kinneret-1	OW	UJG	158	(–207.8)–(–209.2)			
Kinneret-10b	OW	LJG	1006	not monitored			
Tiberias							
Main Spring	OS				0.03–0.04	0	17000
Main Spring 1	OS				0.0002–0.00035	0	18000
Roman Spring	OS				0.001–0.004	0	18000
Holliday Inn	OW	DSG	37	(–208.0)–(–209.0)			
Kikar	OW	DSG	62	(–209.0)–(–212.5)			
Kinneret-2	OW	LJG	108	(–203.0)–(–204.5)			
Ganei Hamat	OW	DSG	40	(–209.0)–(–212.0)			

* OS-onshore spring, OW-observation well, AW-artesian well, OF- offshore well, PW-pumping well.

** The aquifer where the well is screened. UJG-Upper Judea group, LJG-Lower Judea Group, AG-Avdar Group, DSG-Dead Sea Group.

(1) These shallow offshore wells (penetrate about 5 m into the lake's bottom) have similar concentration and hydraulic head trends as nearby onshore springs and wells.

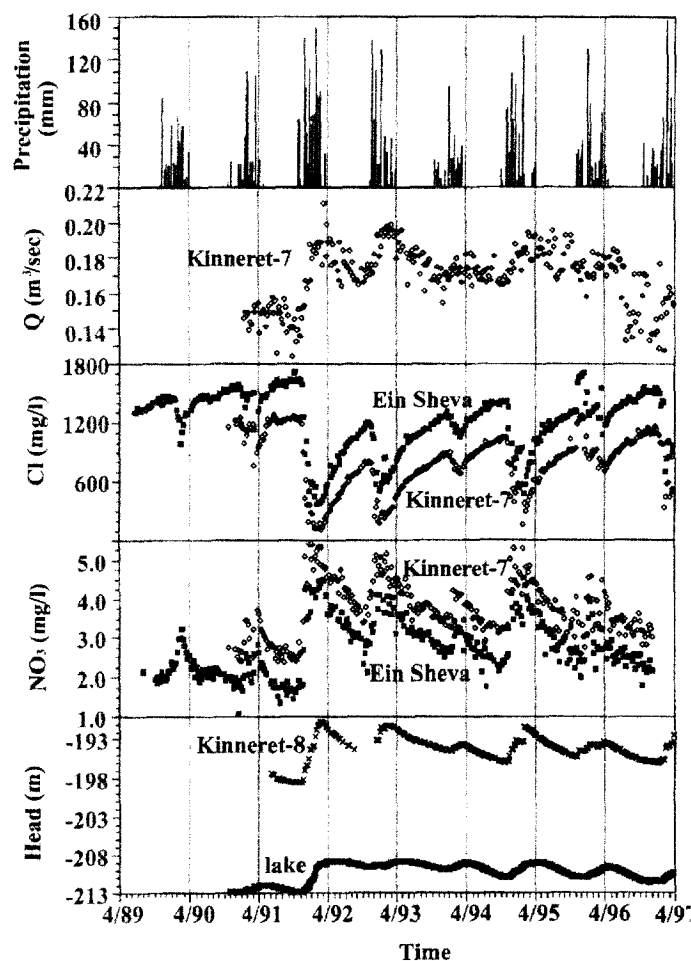


Figure 3. Tabgha Group data including: (a) Weekly measurements of precipitation measured at the Mt. Canaan station (Figure 1b). (b) Discharge in the Kinneret-7 artesian well. (c) Chloride concentration in the Kinneret-7 well and Ein Sheva spring. (d) Nitrate concentrations in the Kinneret-7 well and the Ein Sheva spring. (e) Hydraulic head in the Kinneret-8 well and lake level.

Co. (Simon and Eizik 1991) were used for comparison. Chloride concentration was measured using the standard potentiometric method (Eaton et al. 1995) with an error of 0.5%. Nitrate concentration was measured by the NAS method (Szekely 1975) with a maximum error of 5%. Spring discharge was measured using a magnetic flowmeter within a section of fixed geometry, with a maximum error of 20%, (but in most springs much less than 10%, based on repeated measurements). The absolute elevation of the monitored wells is accurate to about 1 cm confirmed with GPS measurements. This implies that the accuracy of the presented hydraulic heads is in the same order of magnitude. The presented heads are not "equivalent fresh water head"; however, analyzing data in selected wells reveals that results deviate by no more than 5%.

Due to the large amount of data obtained, only temporal data from selected springs and wells within each group of springs are presented.

Results

Tabgha Group

All springs of the Tabgha drainage basin (Figure 1c; Table 1) are similar to each other by means of their temporal chloride and nitrate concentrations, and discharge trends. Spring discharge and

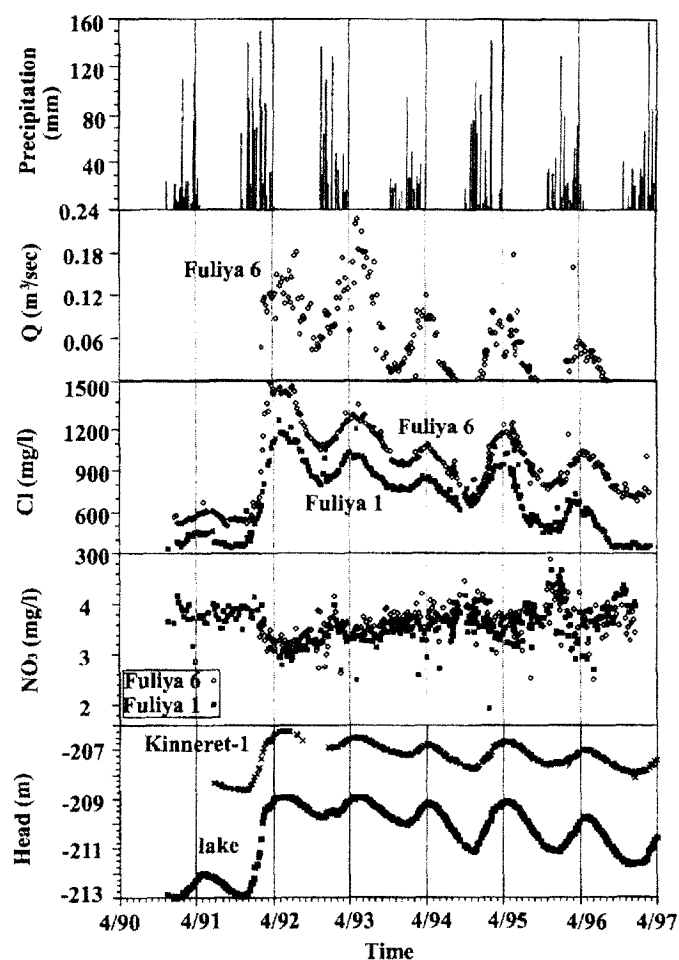


Figure 4. Fuliya Group data including: (a) Weekly measurements of precipitation measured at the Mt. Canaan station. (b) Discharge in the Fuliya-6 spring. (c) Chloride concentration in the Fuliya-6 and Fuliya-1 springs. (d) Nitrate concentrations in the Fuliya-6 and Fuliya-1 springs. (e) Hydraulic heads in the Kinneret-1 and Fuliya A wells and lake level.

nitrate concentrations decrease gradually to a minimum in November and December and subsequently increase rapidly in the rainy season (January and February) (Figure 3). Discharge at Kinneret-7 (artesian well) ranges between 0.12 and 0.20 m³/sec and Ein-Sheva ranges between 0.001 and 0.006 m³/sec. Nitrate concentration varies between 2.5 and 5.5 mg/L in Kinneret-7 and between 2.0 and 4.5 mg/L in Ein-Sheva. On the other hand, chloride concentration has an opposing trend; it increases gradually to a maximum in November and December and then decreases rapidly in the rainy season. Chloride concentration varies between 300 and 1300 mg/L in Kinneret-7 and between 400 and 1500 mg/L in Ein-Sheva. The nitrate concentration increase and chloride concentration decrease were most pronounced during the significantly wetter winter of 1991–1992 (150% of the annual average precipitation in the Sea of Galilee region). The hydraulic head in the Kinneret-8 well is usually about 15 to 18 m above lake level and it varies 1 to 6 m within a year. It rises rapidly in the winter and then declines gradually during the spring and summer. It correlates with spring discharge and nitrate concentration and has an opposing trend to chloride concentration. However, in Kinneret-8 hydraulic head reaches its maximum about two months prior to the lake level and its fluctuation is usually about double compared with the lake level (Figure 3).

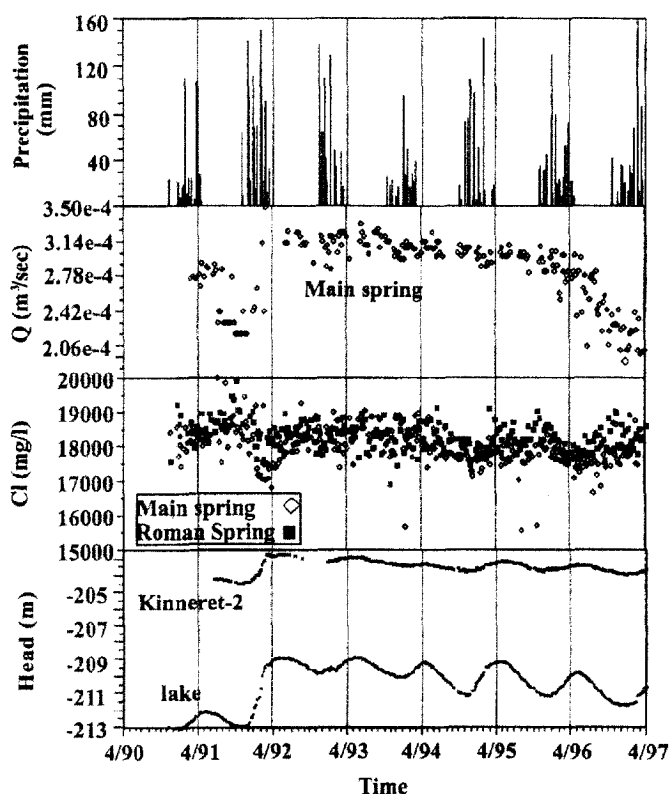


Figure 5. Tiberias Group data including: (a) Weekly measurements of precipitation measured at the Mt. Canaan station. (b) Discharge in the Main Spring 1. (c) Chloride concentration in the Main Spring 1 and the Roman springs. (d) Hydraulic heads in the Kinneret-2 and Kikar wells and lake level.

Offshore Barbutim springs (Figure 1b) are probably connected to the Tabgha system. Hydraulic head and chloride concentrations measured in a few abandoned wells have temporal trends similar to wells and springs in Tabgha and differ from lake level fluctuations (Kahanovitch and Mero 1973).

Fuliya Group

All springs in the Fuliya drainage basin have the same temporal characteristics, and relatively similar discharge and chloride and nitrate concentration values. Discharge increases to maximum in April and May and decreases to minimum in September through November (0 to 0.2 m³/sec in Fuliya-6) (Table 1; Figure 4). In some summers, springs have dried out completely. Chloride concentration varies between 300 to 1200 mg/L in Fuliya-1 and 500 to 1500 mg/L in Fuliya-5 and Fuliya-6. Maximum concentration is in April and May and minimum in September through November. The maximum chloride concentration in Fuliya occurs approximately two months after the minimum concentration in Tabgha, and minimum concentration in Fuliya occurs two months after the maximum in Tabgha. Nitrate concentration in the springs is mostly between 3 and 4 mg/L. The seasonal patterns, well pronounced during 1991/1992 and 1995/1996, increase slightly during the summer and fall and decrease in the winter. Chloride and nitrate concentrations and discharge trends in all springs are in phase with lake level (Figure 4). In Fuliya A and Fuliya B (offshore wells; Figure 1d) the concentration and the trend are similar to onshore springs. The hydraulic head in onshore observation wells (penetrating the upper JGA > 200 m) is always higher than the lake. The trend in these wells is similar to the lake level ($R^2 > 0.9$), but fluctuations are smaller than lake level.

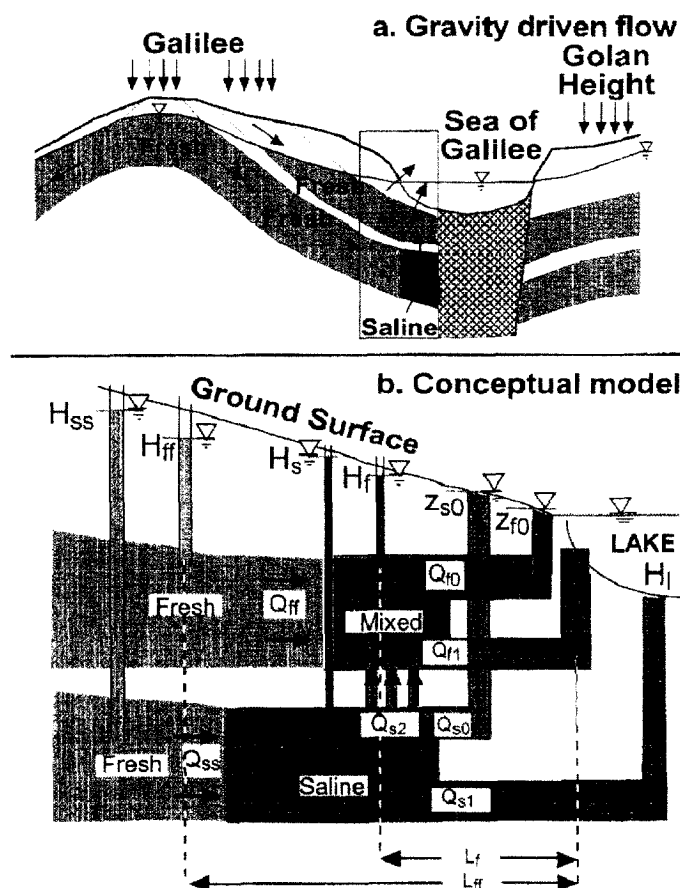


Figure 6. A conceptual model of saline water discharge along the lake's shore. (a) In a cross section including the recharge area in the Galilee Mountains and the discharge area near the Sea of Galilee (after Gvirtzman et al. 1997a). (b) A generalized description of the system, including discharge between the various components (parameters are defined in Table 2).

Tiberias Group

Chloride concentration in the Tiberias springs ranges between 15,000 and 20,000 mg/L, and is nearly constant in each individual spring throughout the year (Table 1; Figure 5). A few sporadic deviations from this general trend have occurred in different wells and springs. The measured nitrate concentration is usually less than 0.1 mg/L, less than the measured error. The hydraulic heads in Kinneret-2 and Kikar wells have an annual variation of less than 2 m, and fluctuations are similar to the trend in Fuliya (in phase with lake level). It reaches maximum in April and May and minimum in September through November. Discharge was measured during the past seven years in Main Spring-1 only but the scatter of the data is large. Partial data from previous years from the Roman Spring indicates a good correlation between discharge and lake level fluctuations, similar to the situation in Fuliya.

Conceptual Model

A unified conceptual model consisting of two confined aquifers is proposed for the Tabgha, Fuliya, and Tiberias systems (Figure 6; Table 2). The lower aquifer corresponds to the Lower Judea and Kurnub Groups and carries saline water characterized by high chloride concentration and low nitrate concentration in the vicinity of the springs. The upper aquifer includes the top JGA and in some cases the unconfined Avdat Group aquifer. It carries fresh water

Table 2 Definition of Parameters Incorporated in the Conceptual Model (Figures 6 and 7)	
Parameter	Description
H_{ss}	Hydraulic head in deep aquifer–fresh water zone
H_{ff}	Hydraulic head in shallow aquifer–fresh water zone
H_s	Hydraulic head in deep aquifer–saline water zone
H_f	Hydraulic head in shallow aquifer–mixed water zone
H_l	Lake level
z_{s0}	The hydraulic head of spring water emerging from the lower saline aquifer
z_{f0}	The hydraulic head of spring water emerging from the mixed water aquifer
Q_{ss}	Discharge of fresh water into the saline water zone within the lower aquifer
Q_{ff}	Discharge of fresh water into the mixed water zone within the upper aquifer
Q_{s0}	Discharge of saline water to an onshore spring
Q_{s1}	Discharge of saline water to an offshore spring
Q_{s2}	Discharge of saline water from the lower aquifer to the zone of mixed water

characterized by low chloride concentration and relatively high nitrate concentration. Westward, in the Galilee, both aquifers have phreatic portions (Figure 1b). The lower fresh water aquifer recharged in the Galilee produces hydraulic pressure on the saline water, trapped in a narrow (east-west direction) zone in the vicinity of lake's shore. Each group of springs is characterized by a distinct temporal trend of discharge and chloride and nitrate concentrations. Also, there is an obvious difference in the distribution of salinity with depth between the Tiberias group and the two other groups of springs.

The conceptual model shown in Figure 6b describes discharge (Q) between different parts of the system, each represented by an arrow and a subscript index (Table 2). Mixing between water from the two aquifers takes place through fractures in a narrow (east-west direction) zone in the vicinity of the lake's shore. Emergence of saline water to the mixing zone (Q_{s2}) results from discharge from the higher hydraulic head in the saline water, H_s , to the lower head in the mixed zone, H_f . Both the saline water aquifer and mixed water aquifer may leak directly to onshore springs (Q_{s0} and Q_{f0} , respectively) and to the lake bottom (Q_{s1} and Q_{f1}). The saline water and mixed water aquifers are drained through a constant head boundary (z_{s0} , z_{f0}), representing onshore springs, and a time varying boundary $H_l(t)$, representing offshore springs. Lateral eastward discharge of fresh water within the lower and upper aquifers are Q_{ss} and Q_{ff} , respectively, and the ground water heads are H_{ss} for the lower aquifer and H_{ff} for the upper aquifer.

Basic physical considerations are applied to simplify the proposed conceptual model for each group of springs. In Tabgha and Fuliya, direct discharge from the saline aquifer to onshore and offshore springs is excluded (Figures 7a and 7b), eliminating Q_{s0} , Q_{s1} , and z_{s0} from their model. This is justified, since there are no springs with high chloride concentrations ($>15,000$ mgCl), and it is not plausible that emerging saline water will cross a fresh water aquifer without being diluted. In Tiberias the absence of the upper mixed aquifer (Figure 7c) eliminates Q_{s2} , Q_{f0} , and Q_{f1} from the system.

In Figure 7, hydraulic heads of the aquifers are presented by observation wells and springs (Table 1; Figures 3 through 5). In Tabgha (Figure 7a), H_{ss} is presented by ground water level in

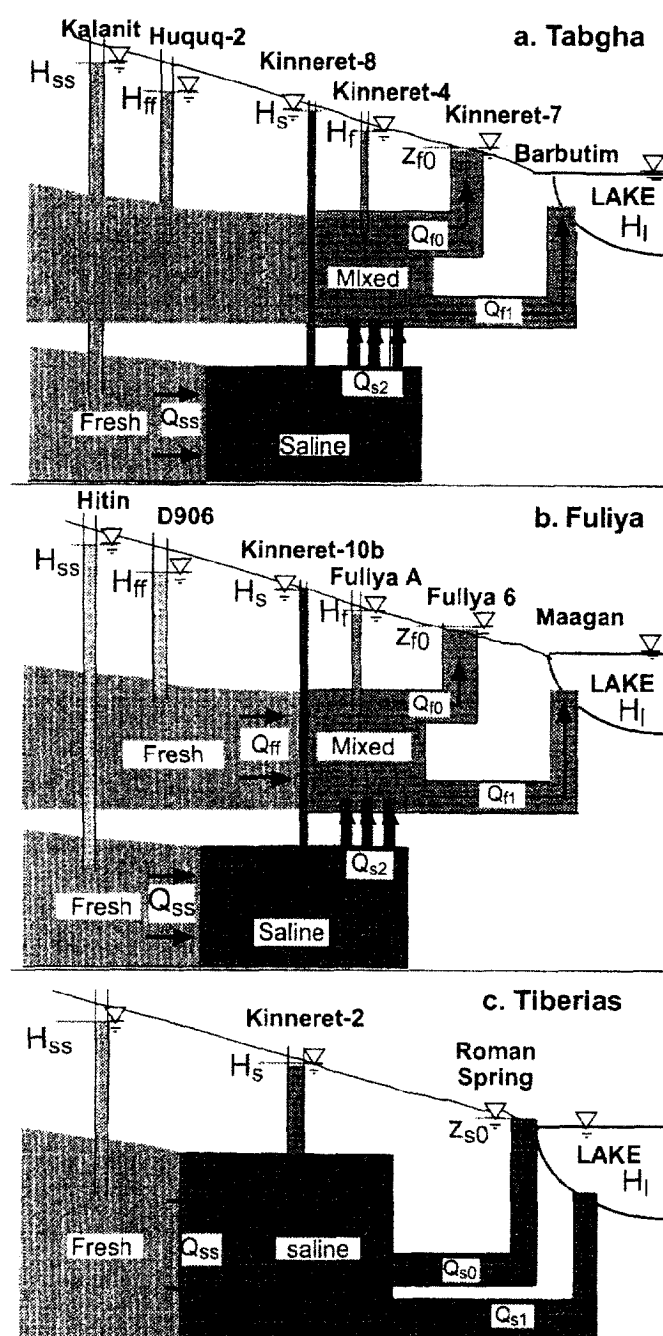


Figure 7. Application of the conceptual model, where the hydraulic heads of the aquifers are presented by selected wells and springs as applied to: (a) the Tabgha Group; (b) the Fuliya Group; and (c) the Tiberias Group, where the upper aquifer is absent. Figures are not to scale.

Kalanit wells, H_s by Kinneret-8 observation well, H_f by Kinneret-4, H_{ff} by Huquq-2. Q_{f0} is obtained from the various springs monitored in Tabgha, and Q_{f1} is attributed to the Barbutim offshore springs. In Fuliya (Figure 7b), H_{ss} is presented by Hitin wells, H_{ff} by D906 and Kinneret-1 wells with similar piezometric heads, H_f is presented by Fuliya A (an offshore spring captured by a large diameter vertical pipe where the piezometric head is always higher than the lake level). Piezometric heads from depths greater than 200 m are not presented since there are no reliable long-term data. However, a few new measurements of ground water head from Kinneret-10b well indicate that it is higher than in shallower aquifers, and follows lake-level patterns. Therefore, the calculated

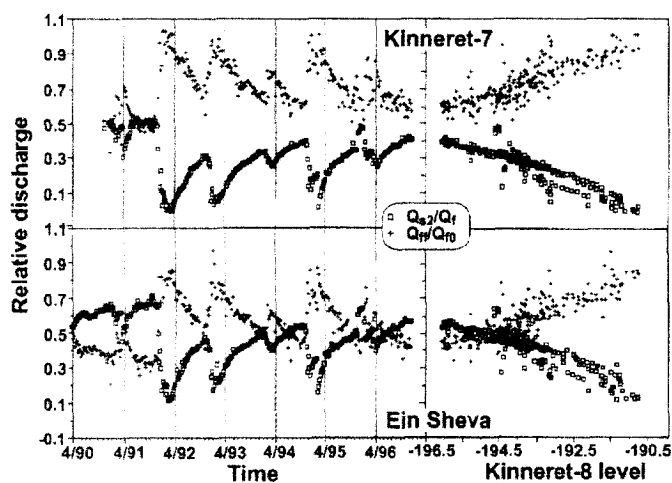


Figure 8. Time dependent relative discharge of the saline aquifer (Q_{s2}) and the fresh water aquifer (Q_{ff}) to Kinneret-7 and Ein Sheva in Tabgha on the left side. The relative discharge as a function of the hydraulic head in the Kinneret-8 well is on the right side.

annual pattern of H_s follows the linear relationship $H_s - H_f \equiv a \cdot H_f + b$, where a and b are constants. In Tiberias (Figure 7c), H_s is presented by Kinneret-2.

Mathematical Model

Mixing of Water in the Springs

Defining the time dependent discharge of fresh water and saline water to the saline springs is an essential requirement in verifying the proposed conceptual model. A mathematical model describing the mixing process was developed in order to find the relative contribution of each endmember as a function of time and ground water level. The process of mixing between two endmembers is actually a gradual process in time and space. Considerations such as horizontal water flow and the actual ion concentration at each depth, as well as many other parameters that vary gradually with depth, cannot be described fully by our approach. However, the mixing process is described by a system of two "lumped" main aquifers, while the calculated concentrations at each aquifer are averaged or lumped numbers that best describe this gradual process.

The analysis is based on the chloride and nitrate concentrations measured in the springs. It was found that in the saline aquifers chloride concentration is at least two orders of magnitude higher than in the fresh water aquifer. On the other hand, the nitrate concentration is usually below detection limit (< 1 mg/L) in the saline aquifers, while its concentration in the saline springs of Tabgha and Fuliya is 1 to 5.5 mg/L.

Water discharge from a single spring (Q_{ff}) is a mixture of ground water from the fresh and saline aquifers. For mathematical formulation, it is assumed that nitrate is supplied only by the fresh water aquifer, and chloride mainly by the saline aquifer. NO_3 is assumed to be conservative in the system since the residence time in the mixed aquifer is less than one day and mostly several hours (Moise 1996).

According to the conceptual model it is assumed that the chloride and nitrate concentrations of the fresh water aquifer are identical for each group of springs, while the chloride concentration for

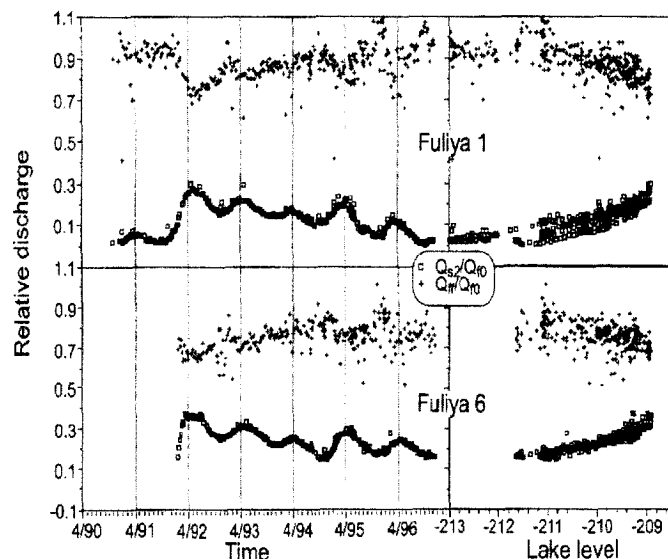


Figure 9. Time dependent relative discharge of the saline aquifer (Q_{s2}) and the fresh water aquifer (Q_{ff}) to the Fuliya-1 and Fuliya-6 springs on the left side. The relative discharge as a function of lake level is on the right side.

a single spring within each group depends on the local conditions of the mixing process (i.e., depth and salinity). The mixing of two sources within a single spring is

$$\begin{aligned} a. & Q_{s2}[Cl]_s + Q_{ff}[Cl]_{ff} = Q_f[Cl]_f \\ b. & Q_{s2}[NO_3]_s + Q_{ff}[NO_3]_{ff} = Q_f[NO_3]_f \\ c. & Q_{s2} + Q_{ff} = Q_{f1} + Q_{f0} = Q_f \end{aligned} \quad (1)$$

where Q_{s2} and Q_{ff} are the leakage discharge from the saline aquifer and the fresh water discharge into the mixed aquifer, respectively; $[Cl, NO_3]_s$ and $[NO_3, Cl]_{ff}$ are the saline water and the fresh water component concentrations, respectively; and $[Cl, NO_3]_f$ is the concentration in the mixed aquifer. It is assumed that the measured concentrations in the saline springs are identical to those in the mixed aquifer, i.e., $[Cl]_{f0} = [Cl]_f$ and $[NO_3]_{f0} = [NO_3]_f$; therefore Equation 1 can be simplified as

$$\begin{bmatrix} [Cl]_s & [Cl]_{ff} \\ [NO_3]_s & [NO_3]_{ff} \\ 1 & 1 \end{bmatrix} \begin{bmatrix} Q_{s2} / Q_f \\ Q_{ff} / Q_f \end{bmatrix} = \begin{bmatrix} [Cl]_{f0} \\ [NO_3]_{f0} \\ 1 \end{bmatrix} \quad (2)$$

The two discharge ratios and four concentration parameters in the coefficient matrix are unknown. In order to find the limits of a feasible physical solution for Equation 2, two constraints were applied: (1) $[Cl]_{ff}$ (in the fresh water aquifer) is within the range 10 to 300 mg/L, as measured in more than 30 fresh ground water samples within the Kinneret basin (Bergelson et al. 1999); and (2) $[NO_3]_s$ (in the saline aquifer) is negligible and thus, assumed zero. From Figure 2 it appears that $[Cl]_s$ should have a value of 15,000 to 18,000 mg/L. Actually using such a value would result in an infeasible solution of Equation 2; therefore we let both $[Cl]_s$ and $[NO_3]_{ff}$ be determined by the optimal solution of Equation 2. The resulting calculated $[Cl]_s$ and $[NO_3]_{ff}$ were assumed to be the concentrations that represent the mixing process for each spring together with $10 < [Cl]_{ff} < 300$ mg/L.

Applying the solution of Equation 2 to the Tabgha springs, $[Cl]_s$ and $[NO_3]_{ff}$ within each spring have a feasible range rather than a single value. The calculated $[NO_3]_{ff}$ is 4 to 7.5 mg/L, similar to the

nitrate concentrations measured in the fresh ground water aquifers around the lake (see Huquq-2 well and Kinar Spring in Table 1). In the Kinneret-7 artesian well the calculated $[Cl]_s$ range (in mg/L) is $2200 < [Cl]_s < 2500$ and in the Ein-Sheva spring it is $2300 < [Cl]_s < 2600$. It should be noted that the calculated $[Cl]_s$ is only 15% to 20% compared with the expected $[Cl]_s$ value of approximately 15,000 mg/L in the deeper parts of the Kinneret-8 well. This result was caused by our simplified mixing process approach, assuming $[NO_3]_s = 0$, and taking into account a one-step mixing process rather than a gradual one. The calculated concentrations probably represent the final stage of saline water dilution.

The relative discharges (i.e., Q_{s2}/Q_{f0} and Q_{f1}/Q_{f0}) from the saline and fresh aquifers to the Kinneret-7 well and the Ein-Sheva spring, obtained by an optimal solution of Equation 2, were plotted versus time and ground water level in Kinneret-8 (Figure 8). The relative contribution of the saline aquifer (Q_{s2}/Q_{f0}) dropped to ~ 0 in Kinneret-7 and ~ 0.1 in Ein-Sheva during the peak piezometric head in Kinneret-8 in the last eight years. During periods of low piezometric head in Kinneret-8 (summer 1991), the relative contribution of the saline aquifer increased to 0.5 and 0.7 in Kinneret-7 and Ein-Sheva, respectively.

In the Fuliya springs, NO_3 concentration seasonal trends are not as well pronounced as in Tabgha. Therefore, the application of NO_3 as a tracer of fresh water is less constrained. Nevertheless, the obvious annual trend observed in 1991/1992 and 1995/1996 (Figure 3), which is in phase with chloride concentration, spring discharge, and lake level, enables the application of the same mixing model as in Tabgha.

The calculated feasible $[Cl]_s$ is 3600 to 4000 mg/L in Fuliya 6, and 3300 to 3700 mg/L in Fuliya 1. $[Cl]_s$ in these springs is only 20% to 25% of the 17,500 mg/L measured in the Kinneret-10b borehole (Figure 2). The calculated feasible $[NO_3]_{ff}$ range is 4.0 to 5.0 mg/L as expected. The relative ground water discharge in the springs plotted versus time and lake level (Figure 9), indicate that the relative contribution of the saline aquifer dropped to ~ 0 in Fuliya 1 and ~ 0.1 in Fuliya 6 during low lake levels (H_f) (beneath 212 m below MSL). During periods in which the lake levels were high (above 210 m below MSL), the relative contribution of the fresh aquifer increased to 0.2 to 0.3 in Fuliya 1 and in Fuliya 6. Note that the mixture in Fuliya includes only a small component of saline water (without NO_3) compared to the large fresh water component, and therefore the NO_3 is only slightly diluted.

The Draining Process

In the following, a set of differential equations describing the draining process of the aquifers (the period of head decline in the summer and fall) and an analytical solution is proposed. The general equations are then modified for each group of springs, considering terms that may be neglected.

We define the discharge Q (L^3/T) from one component of the hydrological system to another as

$$Q = \alpha(H_1 - H_2) \quad ; \quad \alpha = \frac{KA^*}{L^*} \quad (3)$$

$H_1 - H_2$ (L) represents the head difference between the components. The coefficient α (L^2/T) represents the product of the hydraulic conductivity, K (L/T) of the conduit connecting the components, the cross section of flow A^* (L^2), and the inverse of the distance L^* (L^{-1}) between them.

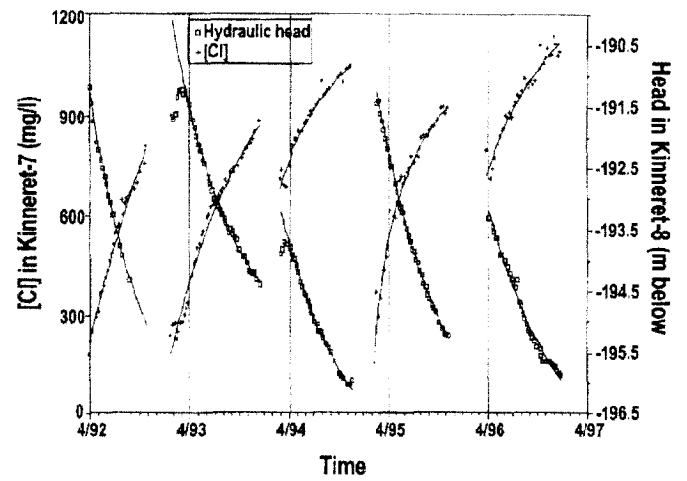


Figure 10. Exponential chloride concentration decrease in Kinneret-7 and hydraulic head increase in Kinneret-8, both located in Tabgha. Symbols are measured data and the curves are exponential functions.

The head of the mixed aquifers (H_f), the discharge from the saline water aquifer to the mixed aquifer (Q_{s2}), the draining discharges of the mixed aquifer to the onshore springs (Q_{f0}), and to the lake bottom (Q_{f1}) are connected through the specified aquifer discharge equation (Bear 1979). A similar equation can be written for the saline water aquifer:

$$\begin{aligned} \text{a. } Q_{f0}(t) + Q_{f1}(t) - Q_{s2}(t) &= -S_f A_f \frac{dH_f(t)}{dt} \\ \text{b. } Q_{s0}(t) + Q_{s1}(t) + Q_{s2}(t) &= -S_s A_s \frac{dH_s(t)}{dt} \end{aligned} \quad (4)$$

where S is the specific storage, and A is the cross section of the drained area (L^2). Combining Equations 4a and 4b, a system of two linear, nonhomogeneous differential equations is given:

$$\begin{bmatrix} D + C_1 & -C_2 \\ -C_3 & D + C_4 \end{bmatrix} \begin{bmatrix} H_f \\ H_s \end{bmatrix} = \begin{bmatrix} I_f(t) \\ I_s(t) \end{bmatrix} \quad (5)$$

where D is a differentiating operator with respect to time (t), and the coefficients C (T^{-1}) are given by

$$\begin{aligned} C_1 &= \frac{\alpha_{f0} + \alpha_{f1} + \alpha_{s2}}{S_f A_f} \quad ; \quad C_2 = \frac{\alpha_{s2}}{S_f A_f} \\ C_3 &= \frac{\alpha_{s2}}{S_s A_s} \quad ; \quad C_4 = \frac{\alpha_{s0} + \alpha_{s1} + \alpha_{s2}}{S_s A_s} \end{aligned} \quad (6)$$

The vector I (L/T) on the right hand side of Equation 5 is given by

$$I_f(t) = \frac{\alpha_{f1} H_1(t) + \alpha_{f0} Z_{f0}}{S_f A_f} \quad ; \quad I_s(t) = \frac{\alpha_{s1} H_1(t) + \alpha_{s0} Z_{s0}}{S_s A_s} \quad (7)$$

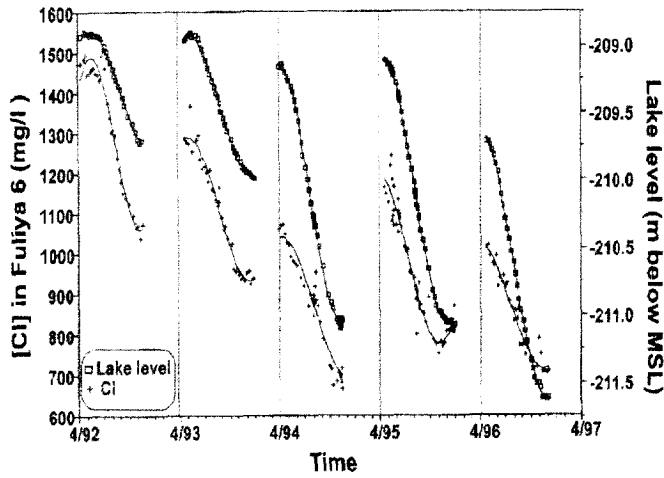


Figure 11. Chloride concentration decrease in Fuliya 6 and the decrease in lake level. Symbols are measured data and the curves are according to a sine-cosine function as in Equations 11 and 12.

By opening Equation 5, two linear, second-order, nonhomogeneous differential equations are formed:

$$\begin{aligned}
 \text{a. } H_f'' + (C_1 + C_4)H_f' + (C_1C_4 - C_2C_3)H_f &= \\
 \frac{\alpha_{f1}}{S_fA_f} H_f' + \left(\frac{\alpha_{f1}C_4}{S_fA_f} + \frac{\alpha_{s1}C_2}{S_sA_s} \right) H_f + \left(\frac{\alpha_{f0}C_4}{S_fA_f} z_{f0} + \frac{\alpha_{s0}C_2}{S_sA_s} z_{s0} \right) & \\
 \text{b. } H_s'' + (C_1 + C_4)H_s' + (C_1C_4 - C_2C_3)H_s &= \\
 \frac{\alpha_{s1}}{S_sA_s} H_s' + \left(\frac{\alpha_{f1}C_3}{S_fA_f} + \frac{\alpha_{s1}C_1}{S_sA_s} \right) H_s + \left(\frac{\alpha_{f0}C_3}{S_fA_f} z_{f0} + \frac{\alpha_{s0}C_1}{S_sA_s} z_{s0} \right) &
 \end{aligned} \quad (8)$$

The solution to Equations 8 is given by

$$\begin{aligned}
 H_f(t) &= B_{1f} \exp(r_1 t) + B_{2f} \exp(r_2 t) + G_f(t) + F_f(z_{f0}, z_{s0}) \\
 H_s(t) &= B_{1s} \exp(r_1 t) + B_{2s} \exp(r_2 t) + G_s(t) + F_s(z_{s0}, z_{f0}) \quad (9)
 \end{aligned}$$

where $r_{1,2}$ are nondimensional time dependent constants of the piezometric head exponential decay:

$$r_{1,2} = \frac{-(C_1 + C_4) \pm \sqrt{(C_1 + C_4)^2 - 4(C_1C_4 - C_2C_3)}}{2} \quad (10)$$

The B coefficients in Equation 9 (L) are determined from the system far boundary conditions; $G(t)$ is a function of the time varying lake level (near boundary conditions); and the coefficient F, which is constant in time, is determined by the piezometric head difference between the aquifers and onshore springs in steady state (i.e., no changes with time in both the far and near boundary conditions). The two exponential terms in the right hand side of Equation 9 are the solution of the homogeneous case, while the other terms in the equation form particular solutions of the nonhomogeneous problem, affected mainly by the lake level and the onshore spring emergence level.

From Equations 3 and 9, discharge from one part of the system to another, as presented in Figure 6b, is given by

$$\begin{aligned}
 \text{a. } Q_{f0}(t) &= \alpha_{f0}[B_{1f} \exp(r_1 t) + B_{2f} \exp(r_2 t) + G_f(t) + F_f(z_{f0}, z_{s0}) - z_{f0}] \\
 \text{b. } Q_{f1}(t) &= \alpha_{f1}[B_{1f} \exp(r_1 t) + B_{2f} \exp(r_2 t) + G_f(t) + F_f(z_{f0}, z_{f0}) - H_f(t)] \\
 \text{c. } Q_{s2}(t) &= \alpha_{s2}[(B_{1s} - B_{1f}) \exp(r_1 t) + (B_{2s} - B_{2f}) \exp(r_2 t) \\
 &\quad + (G_s(t) - G_f(t)) + (F_s(z_{s0}, z_{f0}) - F_f(z_{f0}, z_{s0}))] \\
 \text{d. } Q_{n1}(t) &= Q_{f0}(t) + Q_{f1}(t) - Q_{s2}(t) \quad (11)
 \end{aligned}$$

The presented solution (Equations 9 through 11) was applied to springs in each group. In both Tabgha and Fuliya, α_{s0} , α_{s1} , and z_{s0} were neglected, considering the exclusion of direct discharge from the saline aquifer to the ground surface. In Tabgha it was found that all processes (hydraulic head drawdown, onshore spring discharge, and water salinization) during the drainage period could be described by the exponential part of the solution. Therefore, only the two exponential terms on the right hand side of Equations 9 and 11, and the constants F_f and F_s are considered valid, while the $G_f(t)$ component could be neglected. This type of solution requires small discharge of the offshore springs compared with the onshore springs ($Q_{f1} \ll Q_{f0}$), and relatively small conduits between the mixed aquifer and the lake (i.e., small coefficient α_{f1}) compared with good connection between the mixed aquifer and onshore springs (α_{f0}). Also, the solution requires that saline discharge in the model (Q_{s2}) is well correlated to the hydraulic head of the lower aquifer (H_s), as was actually observed (Figure 8). After H_s reaches its peak at the end of the winter (at $t=0$), the hydraulic head declines exponentially, while salinity in the springs increases exponentially (Figure 10). These changes are possible only if H_f declines prior to H_s , thus causing the head difference $H_s - H_f$ to increase during the drainage period. In Equation 9 this situation may occur for many possible combinations of $r_1 \neq r_2$. Applying an "equivalent fresh water head" to H_s and H_f would further emphasize this pattern, but its magnitude is negligible.

In Fuliya, the area of the springs is characterized by high hydraulic conductivities, as determined by pumping tests in Kinneret-1 (Kahanovitch and Mero 1973), Kinneret-5 (Assouline 1993), and Kinneret-10b (Braester 1997; Lumelsky and Michelson 1997; Rimmer and Berger 1997). This suggests that $r_{1,2}$ have large negative values and, therefore, the exponential terms in Equations 9 and 11 vanish rapidly. Since F is a constant, the right hand side in Equations 9 and 11 vary according to $G(t)$, which indicates that the head in the aquifers depends on lake levels, α_{f1} is large, and Q_{f1} is a significant component of the mixed aquifer drainage. The required private case solution satisfying Equation 8, describing the drawdown trend of lake level and the linear dependence of H_s and H_f with H_f is

$$\begin{aligned}
 \text{a. } H_f(t) &= B_{4f} \sin(\gamma t) + B_{5f} \cos(\gamma t) + B_{3f} z_{f0} \\
 \text{b. } H_s(t) &= B_{4s} \sin(\gamma t) + B_{5s} \cos(\gamma t) + B_{3s} z_{f0} \quad (12)
 \end{aligned}$$

In Equation 12, ground water levels and salinity of the system in Fuliya change as a sinusoidal function of time (Figure 11), at least during the drawdown of the lake's level in the spring and summer (compared with the exponential change in Tabgha). From Equations 3 and 12, discharge from the lower saline aquifer into the mixed aquifer and from the mixed aquifer to onshore springs are

$$\begin{aligned}
 \text{a. } Q_{s2}(t) &= \alpha_{s2}[(B_{4s} - B_{4f}) \sin(\gamma t) + (B_{5s} - B_{5f}) \cos(\gamma t) - (B_{3s} - B_{3f}) z_{f0}] \\
 \text{b. } Q_{f0}(t) &= \alpha_{f0}[B_{4f} \sin(\gamma t) + B_{5f} \cos(\gamma t) + z_{f0}(B_{5f} - 1)] \quad (13)
 \end{aligned}$$

Thus, Equation 13 shows the strong dependence of discharge on lake level.

Discussion

The presented results and analysis shows how two ground water endmembers, each having distinct chloride and nitrate concentrations, actually mix and emerge at the Tabgha and Fuliya springs. Although NO_3 is not a tracer in most natural systems, the data presented for the Tabgha springs (less pronounced for the Fuliya springs) enables it to be considered a tracer of fresh water. In both groups of springs the NO_3 trend is a "mirror" of the chloride trend (Figures 3 and 4). In Tabgha, the NO_3 temporal trend is in phase with rain events as it is affected by far boundary conditions, whereas in Fuliya NO_3 is not in phase with rain events, because it is affected by lake level fluctuations (near boundary conditions). The saline component is located in the lower Judea Group and Kurnub Group aquifers that are partially phreatic in the Galilee, and in deeper aquifers that are confined in the Galilee. The fresh water component is located in the upper JGA and Avdat Group aquifers. In Tabgha the endmember proportion, represented by the ratios Q_{s2}/Q_{f0} and Q_{f1}/Q_{f0} , changes throughout the year in accordance with the head of the lower saline aquifer (H_s) (Figure 8), which, in turn, is directly dependent on circulating ground water. In Fuliya, these ratios are strongly dependent on the lake level (Figure 9), which, in turn, is dependent on snow melt from Mt. Hermon (Figure 1a), evaporation, and pumping. In Tiberias no mixing takes place and only the saline endmember is present.

Previous studies have postulated generic mechanisms for the ascent of saline water to the surface. The "self potential" model was developed on the basis of observations in Tabgha. On the other hand, the "leaching" model was based on observations at Fuliya. Gvirtzman et al. (1997a) postulated that it is unreasonable that the two groups of springs located only 7 km from each other have independent hydrological systems. They claimed that only the "leaching" model takes place, and they attributed different properties of the Kurnub Group aquifer in the recharge area (far boundary conditions) for the observed temporal salinity differences between the groups.

From the data and analysis presented in this study it must be concluded that the seasonal changes of salinity are indeed the result of circulating ground water in both the saline and fresh aquifers (the "leaching" model). However, it should be emphasized that the different hydraulic conductivities between the aquifers and the lake (near boundary conditions) is an additional factor creating different salinization mechanisms between the groups of springs.

Some interesting phenomena may be inferred from the presented set of equations. The solution of the proposed model for Tabgha requires that $H_s - H_f \rightarrow 0$ for $t \rightarrow \infty$. However, during 1988 through 1991 (three consecutive dry seasons, and the closest period we may consider as "infinity", $t \rightarrow \infty$), salinization of the springs was at its peak and kept rising slowly. This result indicates that $H_s - H_f$ approaches a constant greater than zero. This constant term probably expresses a component not included in the proposed model. The most acceptable explanation to this constant is that the fresh water aquifer also drains independently near Tabgha, as was found in Kinar spring (Table 1), to a point lower than the Tabgha saline springs, z_{s0} . Other explanations propose some additional constant pressure applied on the saline water, independent of the water cycle, and therefore might be attributed to the "self potential" model. A geo-thermal source for this overpressure (Mero and Zaltzman 1967)

should be excluded, as the thermal gradients in deep wells in the vicinity are not elevated (Levitte and Olshina 1985). Compaction of sediments as suggested by Mero and Mandel (1963) may certainly be considered. The high average sedimentation rates in the lake, about 1 to 2 mm/yr in the past 5000 years (Thompson et al. 1985) support the idea. Tectonic stress may also be considered—geological mapping (Zaltzman 1964) and small earthquakes in the vicinity (van Eck and Hofstetter 1990) indicate that faulting is active. According to this concept, a strong earthquake should release overpressure and the magnitude of the constant pressure in Equation 11 should be reduced. Even if compaction or tectonic stress applies force on the saline water, it should be remembered that flow rates resulting from such forces are orders of magnitude smaller than the rates resulting from topography-driven flow (Neuzil 1995; Garven 1995). Therefore it is proposed that the magnitude of z_{f0} in Equation 11 is small compared with the force applied by circulating ground water.

Summary and Conclusions

The ground water emerging at the Tabgha and Fuliya springs is a mixture of two endmembers, saline and fresh. The saline endmember emerges from the lower Judea and Kurnub aquifers, and the fresh endmember from the upper Judea and Avdat aquifers. The time dependent mixing of the two endmembers takes place in the top 500 m of the Tabgha and Fuliya springs but does not take place in the Tiberias spring. Gravity-driven flow is the dominant mechanism in these springs, forcing saline ground water from deeper aquifers upward. Compaction or horizontal tectonic stresses may also contribute to the applied pressure in the Tabgha springs, but are minor.

The temporal trends of discharge rate and of chloride and nitrate concentrations within each group of springs are coupled. There is a phase shift of approximately two months between the peaks in Tabgha compared with those in Fuliya and Tiberias. In Tabgha, the trend of these parameters is controlled mainly by recharge in the Galilee (far boundary conditions) and follows an exponential function. In Fuliya and Tiberias, these parameters are mainly dependent on lake level (near boundary conditions) and follow a sine-cosine function. The different patterns are attributed to different hydraulic properties of the discharge area.

As suggested by Goldshmidt et al. (1967) and Gvirtzman et al. (1997a), a practical consequence of this study is that pumping fresh water in the eastern Galilee and reducing the piezometric head of the saline aquifer will decrease salt flux into the lake.

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